PB82-168337

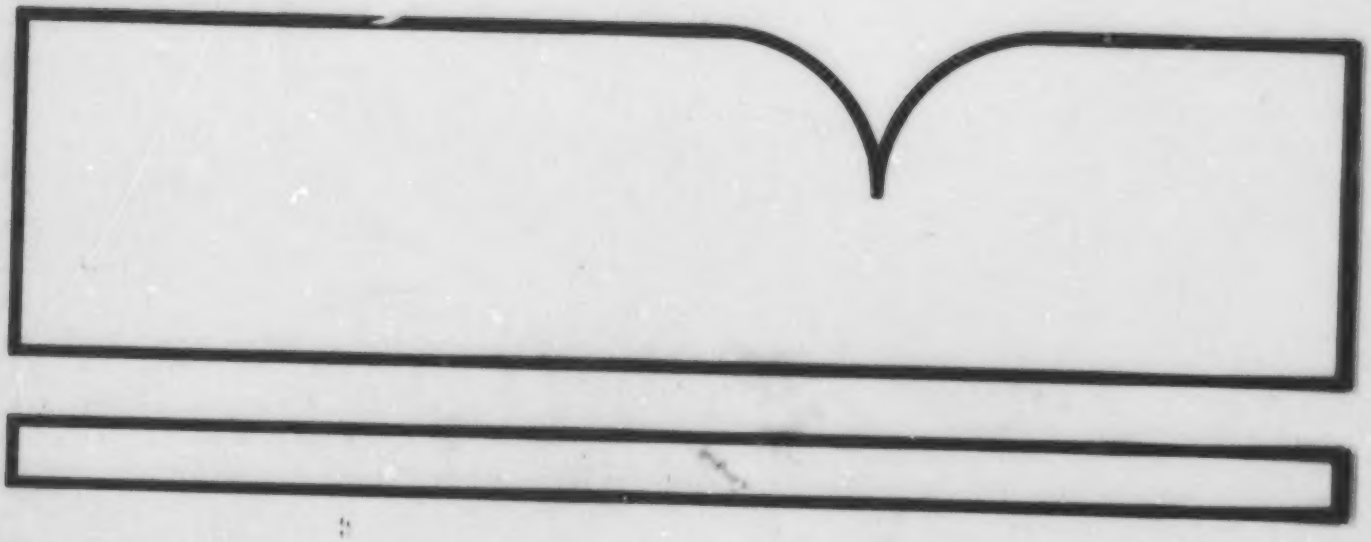
Review of the Environmental Assessment of the Buccaneer Gas and Oil Field in the Northwestern Gulf of Mexico

(U.S.) National Marine Fisheries Service
Galveston, TX

Prepared for

Environmental Protection Agency
Washington, DC

1981



U.S. Department of Commerce
National Technical Information Service
NTIS

50272-101

REPORT DOCUMENTATION PAGE	1. REPORT NO.	2.	3. Recipient's Accession No. PB82 16833 P
4. Title and Subtitle: Review of the Environmental Assessment of the Buccaneer Gas and Oil Field in the Northwestern Gulf of Mexico			5. Report Date: 1981 6. 057028
7. Author(s): Charles W. Caillouet, William B. Jackson, Gregg R. Gitschlag, E. Peter Wilkens, and Gary M. Faw			8. Performing Organization Rept. No.
9. Performing Organization Name and Address: DOC, NOAA, National Marine Fisheries Service Southeast Fisheries Center Galveston Laboratory 4700 Avenue U Galveston, Texas 77550			10. Project/Task/Work Unit No. 11. Contract(C) or Grant(G) No. (C) EPA-IAG-D5-E693-EO (G)
12. Sponsoring Organization Name and Address: Environmental Protection Agency Washington, D.C.			13. Type of Report & Period Covered: Final, 1975-1980 14.

15. Supplementary Notes

16. Abstract (Limit: 200 words)

The environmental assessment of the Buccaneer Gas and Oil Field in the Northwestern Gulf of Mexico is reviewed. The objectives of the environmental assessment were (1) to identify and document the types and extent of biological, chemical and physical alterations of various marine ecosystem components associated with the Buccaneer Field; (2) to determine specific pollutants, their quantities and effects; and (3) to develop the capability to describe and predict fate and effects of Buccaneer Field contaminants. Included in the paper is a general description of impacts associated with presence of the gas and oil field structures as artificial reefs and those associated with gas and oil field contaminants. Also included are references to more detailed reports, publications and data files derived from the investigation, and the agencies, institutions and enterprises contributing to the investigation.

17. Document Analysis a. Descriptors

*Oils
Environmental Impact (Marine)
*Water Pollution (Marine)

b. Identifiers/Open-Ended Terms

*Oil Pollution
*Sediments
*Suspended Particulates
Organic Carbon
Geochemistry
Carbon Isotopes
Benthos (Marine)
Bioassays
Birds (Marine & Migratory)
Fishes (Marine)
Crustaceans (Marine)
Ichthyoplankton (Marine)
Bacteria (Marine)
Biofouling Communities (Marine)
Currents (Hydrography)
Wind (Meteorology)
Hydrocarbons (Petroleum)
Metals
Modeling (Ecosystem)

c. COSATI Field/Group

18. Availability Statement	19. Security Class (This Report)	21. No. of Pages
No restriction on distribution. Available from National Technical Information Service Springfield, Virginia 22161		26
	20. Security Class (This Page)	22. Price

(See ANSI-Z39.18) See Instructions on Reverse

OPTIONAL FORM 272 (4-77)
(Formerly NTIS-35)
Department of Commerce

PB82-168337

Reprinted From The Proceedings of the
THIRTY-THIRD ANNUAL
GULF AND CARIBBEAN FISHERIES INSTITUTE
SAN JOSE, COSTA RICA NOVEMBER 1980

Review of the Environmental Assessment of the Buccaneer Gas and Oil Field in the Northwestern Gulf of Mexico

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RESUMEN

Este trabajo revisa los resultados de cuatro años de estudio en relación con el impacto ambiental del Gas Buccaneer y los Campos Petroleros en el noroeste del Golfo de México. Los objetivos del estudio fueron: (1) el documentarse documentarse de la clase y alcance de las alteraciones biológicas, químicas y físicas en los hábitos pesqueros asociados a los Campos Buccaneer; (2) la determinación de contaminantes específicos, su cuantía y efectos; y (3) desarrollar la capacidad de describir y predecir la suerte y efectos de los contaminantes del Gas Buccaneer y de los campos petroleros. El estudio incluyó la investigación de los siguientes componentes del habitat (o medio) en relación con contaminación crónica, de bajos niveles de hidrocarburos y trazas de metales: (1) arrecifes pelágicos y peces demersos, (2) ictioplancton, (3) macrocrustáceos, (4) comunidades bioincrustantes, (5) bentos, (6) sedimentos y partículas en suspensión, y (7) la columna de agua.

INTRODUCTION

In this paper we provide a retrospective description and review of the environmental assessment of the Buccaneer Gas and Oil Field (Fig. 1) and information required for user access to principal investigators (Table 1), data, and reports and publications (Literature Cited) representing the original sources of research results from which this paper was prepared.

The Buccaneer Field, occupied by Shell Oil Company operations, is located approximately 50 km south southeast of Galveston, Texas, on the continental shelf of the northwestern Gulf of Mexico. It is isolated from other gas and oil fields. Development of the field began with exploratory operations using mobile drilling rigs in 1960. After the sites were selected, two permanent production platforms were erected (Fig. 2). Additional structures (quarters platforms, well jackets and flare stacks; Figs. 2 and 3) and pipelines also are contained within the field.

Increased energy-related development of the continental shelf is anticipated as the United States attempts to reduce its dependency on foreign oil supplies. To obtain information concerning environmental consequences of such development, the US Government is supporting research to document environmental conditions before, during and after gas and oil exploration and production. The environmental assessment of the Buccaneer Field was one such research project, funded by the US Environmental Protection Agency (EPA), and conducted by the US Department of Commerce, National Oceanic and Atmospheric Administration (NOAA), National Marine Fisheries Service (NMFS) and its contractors (Table 1).

The environmental assessment of the Buccaneer Field was initiated in November 1975 and ended in September 1980. Its major products were (1) Annual Reports and

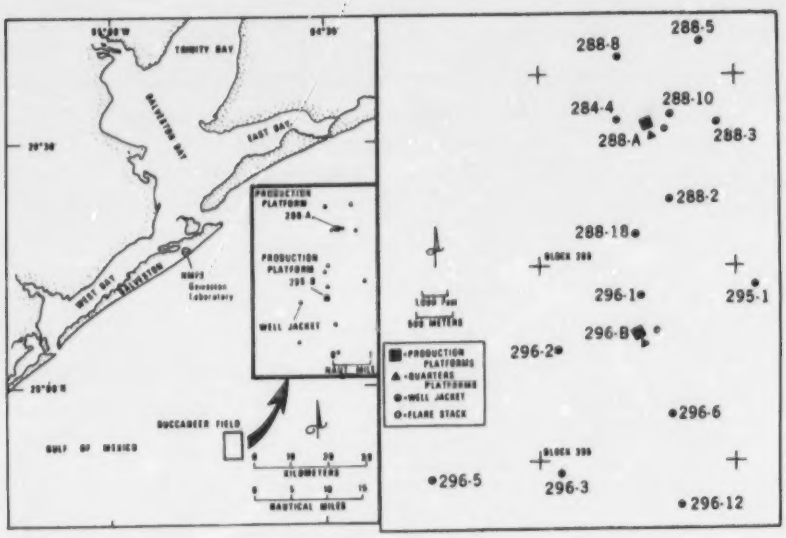

Figure 1. (Left) Location of the Buccaneer Field.

Figure 2. (Right) Shell Oil Company's alphanumerical identification of the Buccaneer field structures.

Milestone Reports to EPA (Literature Cited), copies of which are available from the National Technical Information Service (NTIS), (2) data files which are available from the NOAA Environmental Data and Information Service (EDIS) and (3) published research papers by participating investigators (Literature Cited).

The Buccaneer Field project is an example of an environmental assessment of impacts of chronic, low-level contamination associated with an offshore gas and oil production operation in a long-established field. No major spills have been reported from the Buccaneer Field, though occasional minor spills have been documented (Gallaway et al., 1976). Operations began with the production of oil, but significant quantities of gas were located, and gas production eventually predominated. The primary source of contaminants from the production operations is the produced brine or formation water, a saltwater solution produced in the process of extracting gas and oil. The rate of discharge of produced brine was variable, but was estimated to average 2.5 l/sec (Gallaway, 1980). In addition to containing trace quantities of petroleum hydrocarbons and metals, the produced brine contains large quantities of elemental sulfur, requiring use of biocides to inhibit populations of sulfur-reducing bacteria, which produce highly corrosive metabolites. Except for its high sulfur content, the produced brine from the Buccaneer Field could be considered typical of producing fields in the Gulf of Mexico.

Even though it is generally difficult to demonstrate cause and effect relationships with an environmental assessment when unusual or unexpected changes are detected in an ecosystem, failure to detect effects should not automatically be construed to mean that there are no effects. Detection of effects depends heavily

Table 1. List of participating principal investigators contributing to the environmental assessment of the Buccaneer Field.

J.B. Anderson, Department of Geology, Rice University (RU), Houston, Texas
R.S. Armstrong, NMFS, Northeast Fisheries Center (NEFC), Atlantic Environmental Group (AEG), Narragansett, Rhode Island
G.D. Aumann, Department of Biology, University of Houston (UH), Houston, Texas
K.N. Baxter, NMFS, Southeast Fisheries Center (SEFC), Galveston Laboratory, Galveston, Texas
E.W. Behrens, Geophysics Laboratory, University of Texas (UT), Marine Science Institute, Galveston, Texas
J.M. Brooks, Department of Oceanography, Texas A&M University (TAMU), College Station, Texas
L.J. Danek, Hazelton Environmental Sciences Corporation, Inc. (HES), Northbrook, Illinois
D. Emiliani, NMFS, Southeast Fisheries Center (SEFC), Galveston Laboratory, Galveston, Texas
J.H. Finucane, NMFS, Southeast Fisheries Center (SEFC), Panama City Laboratory, Panama City, Florida
N. Fotheringham, Department of Biology, University of Houston (UH), Houston, Texas
K. Fucik, Science Applications Inc. (SAI), Boulder, Colorado
B.J. Gallaway, LGL Ecological Research Associates, Inc. (LGL), Bryan, Texas
D.E. Harper, Jr., Texas A&M University (TAMU), Moody Marine Laboratory, Galveston, Texas
H. Holley, NMFS, Southeast Fisheries Center (SEFC), National Fisheries Engineering Laboratory (NFEL), Bay St. Louis, Mississippi
R.L. Howard, LGL Ecological Research Associates, Inc. (LGL), Bryan, Texas
J.A. Martin, NMFS, Southeast Fisheries Center (SEFC), Galveston Laboratory, Galveston, Texas
B.S. Middleditch, Department of Biophysical Sciences, University of Houston (UH), Houston, Texas
F. Mitchell, NOAA, Environmental Data and Information Service (EDIS), Washington, D.C.
K. Savastano, NMFS, Southeast Fisheries Center (SEFC), National Fisheries Engineering Laboratory (NFEL), Bay St. Louis, Mississippi
R.K. Sizemore, Marine Science Program, Department of Biology, University of Houston (UH), Galveston, Texas
G. Smedes, Environmental Research and Technology, Inc. (ERT), Seattle, Washington
J.B. Tillery, Southwest Research Institute (SRI), San Antonio, Texas
L. Trent, NMFS, Southeast Fisheries Center (SEFC), Panama City Laboratory, Panama City, Florida
I.K. Workman, NMFS, Southeast Fisheries Center (SEFC), Galveston Laboratory, Galveston, Texas
Z.P. Zein-Eldin, NMFS, Southeast Fisheries Center (SEFC), Galveston Laboratory, Galveston, Texas

upon the statistical adequacy of the sampling pattern, frequency, methods and equipment as well as the accuracy and precision of methods used to analyze the samples. Collectively, these factors determine the detection limits or the sensitivity levels of the methods used. Therefore, failure to detect effects can be the result of two

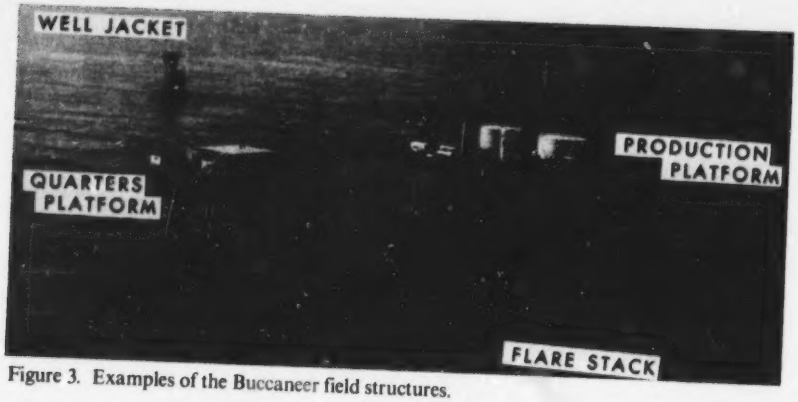

Figure 3. Examples of the Buccaneer field structures.

distinctly different conditions: (1) when there are no effects, or (2) when the effects are too small to be detected by the particular sampling and analysis procedures used. When statistically significant effects are detected by the particular sampling and analysis procedures, they still must be interpreted in terms of their practical significance with regard to the seriousness of the detected change or difference. In our review, we mention situations in which no effects were detected as well as those in which some effects were detected, without making judgments as to their practical significance. Those judgments will be left to the technical reports and publications written by project participants (see Literature Cited) and to those who will read and use this detailed information. The reader is referred to Hunter (1980) for further information concerning problems of scientific measurement.

A symposium covering Buccaneer Field studies was held on October 8-9, 1980, as part of the technical program of EXPOCHEM '80 in Houston, Texas. It is anticipated that the proceedings of that symposium will be published early in 1981 (Dr. Brian S. Middleditch, University of Houston, Texas, personal communication, January 1981).

We emphasize that the results presented herein were excerpted entirely from published reports and papers authored by participating investigators (Table 1 and Literature Cited), and do not represent research conducted by the authors of this paper, with one exception; Gary Faw contributed to the bacterial studies as a graduate student at the University of Houston. Our contributions to the environmental assessment of the Buccaneer Field have been through project planning and management. Because this is a review paper, the reader is referred to the Literature Cited as a source of technical details of the investigation.

OBJECTIVES

Overall objectives of the environmental assessment of the Buccaneer Field were: (1) to identify and document the types and extent of biological, chemical and physical alterations of various marine ecosystem components associated with the Buccaneer Field, (2) to determine specific pollutants, their quantities and effects, and (3) to develop the capability to describe and predict fate and effects of Buccaneer Field contaminants.

Approach

A brief pilot study (Table 2) was conducted in November and December 1975 (Harper, Scrudato and Giam, 1976) to determine whether or not the Buccaneer Field was an appropriate site for such an environmental assessment. Levels of hydrocarbons and peculiarities in distribution of sediment types and benthic infauna were found to be of sufficient concern to warrant further investigation. The pilot study was followed by a 1-year survey in 1976-1977, which compared environmental conditions in the Buccaneer Field with those of adjacent "control" areas. Following a project review, EPA, NOAA and NMFS concluded that environmental effects of the Buccaneer Field were not likely to be detected through such a survey. Beginning in 1977, and continuing until the end of this environmental assessment, investigations were focused within the Buccaneer Field to compare conditions around production platforms, quarters platforms and flare stacks (which release various discharges) with those around well jackets (which do not release effluents) (Fig. 3).

RESULTS

Fishes. Gallaway (1980) summarized the results of investigations of pelagic, reef and demersal fishes associated with the Buccaneer Field. Fish were observed or sampled by a variety of techniques including direct censuses by divers, underwater photography, trapping, trolling, trawling, gillnetting, longlining, hook-and-line fishing, airlift and other diver-operated collecting devices, and mark-release-recapture experiments. These techniques provided qualitative and quantitative measurements of fish population characteristics, including species and size composition, abundance, food and feeding habits, trophic relationships, health and weight-length relationships.

Production platforms and other structures in the Buccaneer Field served as artificial reefs around which fish aggregated (Gallaway, 1980). The structure-associated fish were either seasonal transients or residents. Important seasonal transients were the warm-season, pelagic predators and their plankton- and/or particulate-feeding prey. Pelagics included king mackerel (*Scomberomorus cavalla*), cobia (*Rachycentron canadum*), bluefish (*Pomatomus saltatrix*), little tunny (*Euthynnus alletteratus*), dolphin (*Coryphaena hippurus*), various sharks (Squaliformes), blue runner (*Caranx crysos*), sharksuckers (Echeneidae), and crevalle jack (*Caranx hippos*). Prey species included Spanish sardine (*Sardinella anchovia*), scaled sardine (*Harengula pensacolae*), and rough scad (*Trachurus lathami*). This assemblage of transient fishes appeared to be attracted to the structures intrinsically.

Resident species included those dependent upon the structure-associated fouling community for both food and cover and those apparently attracted to the structures for cover alone (Gallaway, 1980). Representatives of the former group included sheepshead (*Archosargus probatocephalus*), blennies (Blenniidae), triggerfish (*Balistes capriscus*), amberjacks (*Seriola* spp.), damselfishes (Pomacentridae), butterflyfish (*Chaetodon ocellatus*), angelfishes (Chaetodontidae), small sea basses (Serranidae), cubbyu (*Equetus acuminatus*) and wrasses (Labridae). Those of the latter group included Atlantic spadefish (*Chaetodipterus faber*), tomtate (*Haemulon aurolineatum*), Caribbean red snapper (*Lutjanus campechanus*) and

Table 2. Topics and responsible organization or agency contributing to the environmental assessment of the Buccaneer gas and oil field (see Table 1 for explanation of acronyms)

Abbreviated Topics (Responsible organization or agency)	1975	1976	1977	1978	1979	1980
Project Management (NOAA/NMFS/SEFC Galveston Lab)	X	———	———	———	———	X
Data Management (NOAA/NMFS/NFEL & NOAA/EDIS)	X	———	———	———	———	X
Pilot Study (TAMU)	X-X					
Sediments and Suspended Particulates						
Sedimentology, Geochemistry and Nepheloid Layer (RU)		X	———	X		
Carbon Isotopes & Organic Carbon (UT)		X	——	X		
Surficial Sediments and Suspended Particulate Matter (TAMU)				X	———	X
Benthos						
Macro- and Meiobenthos (TAMU)		X	——	X		
Bioassays						
Shrimp (NMFS/SEFC Galveston Lab)			X	——	X	
Birds						
Migratory and Marine Birds (UH)		X	——	X		
Fishes and Macro-Crustaceans						
Demersal Fishes & Macro-Crustaceans (NMFS/SEFC Galveston Lab)		X	——	X		
Pelagic Fishes & Demersal Fishes & Macro-Crustaceans (NMFS/SEFC Galveston Lab. & Panama City Lab)		X	———	X		
Pelagic, Reef & Demersal Fishes & Macro-Crustaceans (LGL)				X	———	X
Ichthyoplankton (NMFS/SEFC Panama City Lab.)		X	———	X		
Bacteria (UH)			X	———	———	X
Fouling Communities						
Effects of Structures (UH)		X	——	X		
Effects of Structures/Fouling Communities (LGL)			X	———	———	X
Circulation & Hydrography						
Hydrography/Circulation Patterns (NMFS/SEFC Galveston Lab. & NMFS/NEFC/AEG)		X	———	X	X	—X
Currents & Hydrography (HES)				X	——	X
Hydrocarbons						
Hydrocarbons, biocides and Sulfur (UH)		X	———	———	———	X
Volatile Hydrocarbons (TAMU)						X —— X

Table 2. Continued

Abbreviated Topics (Responsible organization or agency)	1975	1976	1977	1978	1979	1980
Trace Metals						
Heavy Metals (RU)		X	-------	X		
Trace Metals (SRI)				X	-------	X
Modeling						
Ecological Modeling (LGL)			X	---	X	
Hydrocarbon Modeling (UH)			X	---	X	
Source, Fate and Effects Modeling (SAI)				X	---	X
Hydrodynamic Modeling (ERT)				X	---	X
Transport and Dispersion Modeling (NMFS/NEFC/AEG)					X	--- X

groupers (Serranidae).

Two seasonal assemblages (summer and winter) of demersal finfishes were observed; they were separated by transition assemblages during spring and autumn (Gallaway, 1980). The summer assemblage, characterized by low abundance and few species, was dominated by longspine porgy (*Stenotomus caprinus*). The winter assemblage was characterized by high abundance and many species.

Aggregation of fishes around the Buccaneer Field structures enhanced their availability or vulnerability to capture by recreational fishermen and divers (Gallaway, 1980). This was also true of oil field structures off the coast of Louisiana (Dugas, Guillory and Fischer, 1979). Creel censuses and mark-recapture experiments indicated that red snappers were subjected to heavy fishing pressure (Gallaway and Martin, 1980). Age Classes I and II dominated the collections, and no fish older than Age Class IV was collected. Once recruited to the artificial habitats represented by Buccaneer Field structures, red snapper showed only limited movements, appearing to be "habitat faithful." Heavy recreational fishing on red snappers at petroleum platforms is of major concern as this may be contributing to the present over-exploited status of red snapper stocks in the Gulf of Mexico (Gallaway, 1980).

Beyond a radius of a few meters from the produced brine outfalls, Gallaway (1980) discerned no cause and effect relationship between produced brine discharge from production platforms and composition of fish communities. He attributed this to rapid dilution and dispersion of the discharged brine.

Ichthyoplankton. Anchovies (Engraulidae), drums (Sciaenidae) and flatfishes (Bothidae) were the most abundant taxa represented in fish larvae collected in the Buccaneer Field with bongo nets (Finucane et al., 1979). The abundance of eggs of eels (Anguilliformes), dragonets (Callionymidae), herrings (Clupeidae), anchovies, drums, mackerels (Scombridae) and soles (Soleidae) indicated that these groups spawned in the Buccaneer Field. However, neither eggs nor larvae of reef fishes were abundant in or near the field. No effects of production operations or discharges were discerned from patterns of abundance and distribution of ichthyoplankton derived from bongo net sampling.

Benthos. Harper (1977) described the distribution and abundance of benthic

meio- and macro-fauna in the Buccaneer Field. The dominant meio-faunal taxa were Nematoda, Foraminifera and Harpacticoida. The lowest meio-faunal abundance occurred in autumn. There was no clear relationship between proximity to production platforms and meio-faunal abundance in sediment samples taken in the Buccaneer Field.

Abundance and diversity of benthic macro-fauna appeared positively correlated with bottom water temperature which changed seasonally (Harper, 1977). Dominant benthic macro-faunal taxa included Polychaeta and Amphipoda. Benthic macro-faunal population density appeared depressed within a radius of 50 m from the production platforms as compared to the surrounding area. Harder substrate near production platforms may have been unsuitable habitat as compared to soft muddy sands observed elsewhere in the field, but Harper (1977) was not able to rule out possible effects of contaminants from metal debris below these platforms or produced brine discharge as possible causes.

Demersal Macro-crustaceans. Demersal macro-crustaceans were sampled by trawling (Gallaway, 1980). Sugar shrimp (*Trachypenaeus similis*) dominated the winter collections. Commercially important brown shrimp (*Penaeus aztecus*) and white shrimp (*Penaeus setiferus*) were not dominant during any season, although brown shrimp were relatively abundant during the fall. Commercial shrimping was seldom observed within the Buccaneer Field but was active during summer and fall in the silty-sand area to the east of the Buccaneer Field. No effects of production operations or discharges were discerned from patterns of abundance and distribution of demersal macro-crustaceans derived from the trawl sampling.

Fouling Communities. Gallaway (1980) summarized studies of the fouling community of the Buccaneer Field and the effects of produced brine discharge on this community. Scrapings, underwater photogrammetry, and recolonization and respirometry experiments were employed to determine fouling community composition, biomass, production, oxygen consumption, feeding habits and condition. The fouling community on Buccaneer Field structures was both diverse and abundant, and was composed of two main components: (1) shelled organisms, and (2) "mat" producing organisms. Certain cryptic fauna were associated with each component. The large Mediterranean barnacle (*Balanus tintinnabulum*) dominated the fouling community, covering more than 75% of the metal substrate of Buccaneer Field structures. This dominance was uncharacteristic in that this barnacle species has been reported as incidental in the Gulf of Mexico, but it may be the dominant barnacle on offshore platforms from southwest Louisiana to the Buccaneer Field (Gallaway, 1980). Large clusters of this barnacle were broken from the structures and sank to the bottom during periods of heavy seas or strong currents and formed a major component of the rubble observed beneath the structures. Sheepshead, triggerfish and stone crabs (*Menippe mercenaria*) preyed upon the barnacles. The barnacle community provided a habitat for cryptic fauna such as pistol shrimp (*Synalpheus fritzmuelleri*), stone crab, blennies and polychaetes. Barnacles also provided additional substrate for colonization by mat-formers.

The mat-forming component of the fouling community contained macro-algae (mostly green and red), sponges, bryozoans and hydroids (Gallaway, 1980). The algae represented a relatively small portion of the fouling community biomass, and were more abundant in summer than in winter. The faunal component of the mat,

especially the stalked bryozoan (*Bugula neritina*) and the hydroid (*Tubularia crocea*) exhibited high abundance during winter and low abundance in summer and autumn. The faunal components of the mat community, also filter feeders, were fed upon by sheepshead, triggerfish and small reef fishes. During the spring decline in hydroid abundance, hydroid stalks suspended in the water provided an important food for Atlantic spadefish. Bushy hydroids and bryozoans provided habitat for amphipods, copepods and brittle stars, which exhibited high abundance in winter and declined in abundance during warm seasons, and provided food for sheepshead, triggerfish, blennies and small reef fishes.

During all seasons, fouling community biomass was lower near the bottom than near the water surface (Gallaway, 1980). Produced brine discharge had a detrimental influence on biomass and production rate of the fouling community within a vertical distance about 1 m and a horizontal distance about 10 m from the point of impact of discharged brine with the water surface. This zone of detrimental influence was characterized by virtual absence of large living barnacles, though small (usually dead) barnacles sometimes could be found. Worst-case conditions for the fouling community in this zone apparently occurred more frequently in spring through autumn than during winter, when turbulent mixing enhanced rapid dilution and dispersion of brine discharge. Barnacles collected immediately below the outfall from the sewage treatment facilities on the quarters platforms were in better condition (higher weight to volume ratio) than those in other areas.

Toxicity Bioassays on Shrimp. Zein-Eldin and Keney (1979) conducted 96-h, static, acute toxicity bioassays on juvenile brown and white shrimp, using various dilutions of produced brine discharge in artificial seawater. The observed 3-fold range in 96-h LD_{50} probably resulted from wide variability in composition of the produced brine as well as in methods and duration of its storage before the tests. LD_{50} ranged between 3,000 and 10,000 ppm (v/v). Feeding tests with artificial diets soaked in discharged produced brine suggested that such diets predisposed the shrimp to greater mortality in subsequent acute toxicity tests.

Bacteria. Sizemore and Olsen (1980) reviewed the investigations of bacterial populations associated with seawater, suspended particulate material, sediment and fishes collected in the Buccaneer Field. Taxa and population numbers showed no major differences between the Buccaneer Field and a control site about 9 km north of the field. There were no consistent differences among sampling locations in bacterial diversity or biomass, but seasonal variations occurred. In particular, *Vibrio* sp. exhibited blooms in winter and spring. Of the total population of bacteria in the water column, the majority was associated with suspended particulate matter and 90% with particles 3 μm or larger in diameter. *Vibrio, Pseudomonas, Aeromonas* and *Acinetobacter* predominated, both in sediment and fish samples. *Vibrio* sp. were commonly associated with healthy fish. It also was commonly associated with diseased Atlantic spadefish exhibiting external lesions and fin rot (Gallaway and Martin, 1980). However, *Aeromonas hydrophilia* was consistently associated with diseased Atlantic spadefish collected in the Buccaneer Field.

Oil degrading and sulfur oxidizing bacteria were more abundant in sediments within the Buccaneer Field than in those at the control site (Sizemore and Olsen, 1980). Sulfate reducing bacteria were especially abundant in sediments near production platforms. Bacterial isolates from the Buccaneer Field grew readily in

diluted, produced brine discharge (filter-sterilized), and some were stimulated by high concentrations of the brine. Mixed cultures and some pure cultures of Buccaneer Field bacteria degraded the alkane fraction of diluted Buccaneer condensate (filter-sterilized). The alkane degrading capacity of mixed cultures composed of isolates collected during autumn-winter was lower than that of mixed cultures composed of isolates collected during spring-summer.

During the winters of 1977-1978 and 1978-1979, Gallaway and Martin (1980) observed a disease epidemic in Atlantic spadefish in the Buccaneer Field. The disease was characterized by large, external lesions, varying degrees of fin rot, and presence of the fish pathogen *Vibrio*. No lesions or fin rot were observed in Atlantic spadefish collected at a "control" site, around the sunken vessel V.A. FOGG, approximately 24 km south of the Buccaneer Field. Gallaway and Martin (1980) concluded that these epidemics were the result of activity by opportunistic pathogens during a period of seasonal stress in the Atlantic spadefish, associated with a change in feeding habits from plankton to suspended particulates derived from the fouling community, gonadal development, low temperatures and rough seas. Whether or not the external infections of Atlantic spadefish were related to Buccaneer Field contaminants was problematical, even though the disease epidemic was not observed at the control site. However, chronic low-level exposure of mullet (*Mugil cephalus*) to crude oil contaminants in an estuarine pond has been shown to alter the bacterial flora on this species and to enhance populations of *Vibrio* sp. responsible for fin erosion (Minchew and Yarbrough, 1977; Giles, Brown and Minchew, 1978). Fatty infiltration of the liver also was pronounced in Atlantic spadefish in autumn and winter (Gallaway and Martin, 1980).

Suspended Particulate Matter. Brooks et al. (1980b) summarized investigations of suspended particulate matter in the Buccaneer Field. Observations included total suspended matter (TSM), clay mineralogy, particulate organic carbon (POC), adenosine triphosphate (ATP), energy charge ratio, stable carbon isotope ratios (δ^{13}C[POC]), chlorophyll *a*, phaeophytin, calcium carbonate and particle size.

There were wide spatial and temporal variations in quantity and composition of the suspended particulates. Large nepheloid (cloudy) layers formed by suspended bottom sediments were usually present near the bottom below the thermocline associated with temperature stratification, except when complete vertical mixing (e.g., during winter) resulted in high TSM throughout the water column. Thermal stratification during all seasons, except winter, probably provided a barrier to introduction of Buccaneer produced brine contaminants into the sediments near the production platforms. Smaller, mid-depth nepheloid layers observed in summer were associated with pycnoclines. Surface nepheloid layers observed in spring resulted from coastal freshwater runoff. Clay minerals (smectite in summer, and illite and kaolinite in other seasons) usually dominated the suspended particulates.

ATP, an index of living cellular material, indicated that phytoplankton, zooplankton or bacteria represented 20-30 % of the suspended particulates and dominated the organic fraction (Brooks et al., 1980a). Significant concentrations of non-cellular carbon were observed in the particulates only when there was a large, low-salinity lens at the surface or during phytoplankton blooms (indicated by chlorophyll *a* and phaeophytin) associated with increased dissolved organic carbon

concentrations. Calcium carbonate levels, probably originating from carbonate exoskeltons of organisms, were typically low during all seasons, and represented an insignificant fraction of the TSM. Dissolved silicate, phosphate, nitrate and nitrite levels were typical of Gulf inner shelf waters. Energy charge ratios showed no discernible pattern. Stable carbon isotope values for POC were usually typical of oceanic values and gave no evidence for major contributions by terrestrial sources or organic contamination. In autumn, near-bottom values indicated an increased terrestrial POC component from resuspended bottom sediments, and this corresponded to the presence of a large nepheloid layer. Sediment traps attached to the legs of production platforms at various depths collected fine sediments as well as fecal pellets, bones and scales of fishes, barnacle molts, tissue and shell debris, bryozoans, algae and metal flakes (Anderson et al., 1979).

Brooks et al. (1980a) detected no measurable alterations in composition of suspended particulates or in biological activity (as measured by chlorophyll *a*, phaeophytin, ATP and energy charge ratios) in the water column that could be attributed to proximity of Buccaneer Field production platforms or discharges.

Sediments. The Buccaneer Field is a highly dynamic and passive sedimentary environment in which relict sediments, consisting of calcareous shell hash, silts and clays of the Beaumont Formation, are being redistributed across the sea floor (Anderson, Schwarzer and Clark, 1977). The Buccaneer Field is typical of Gulf coast fields in that its production comes from traps created by tectonic activity associated with a salt dome. High resolution seismic profiling indicated that the area contained subsurface faults that influenced surficial sediment patterns. For example, the sediments were displaced to the north of a fault northeast of the Buccaneer Field. Wide variations in textural properties of these sediments reflected scouring and redeposition of ancient sediments. The sandy composition of the sediments indicated prevalence of high energy bottom conditions, which were probably sufficient to re-suspend and disperse from the field most contaminants deposited beneath the production platforms.

Radiocarbon and Pb-210 measurements suggest that erosion predominated over deposition in the Buccaneer Field, especially near production platforms where more than 1 m of sediment may have been eroded (Behrens, 1977; Brooks et al., 1980a). Sediment total organic carbon concentrations exhibited a gradient of decrease with distance from the production platforms, which was attributed to the high biological production associated with the platforms rather than to Buccaneer Field organic contaminants. Stable carbon isotope ratios and results of radiocarbon dating of sediments did not indicate contamination by petroleum hydrocarbons.

Sediment calcium carbonate concentrations were anomalously high beneath and near production platforms, suggesting high productivity by organisms containing calcium carbonate (Brooks et al., 1980b). Barite, a residual of drilling muds, was detected in a few samples near the production platforms. Smectite was the most abundant clay fraction in the surficial sediments, followed by lesser and approximately equal amounts of illite and kaolinite. Smectite concentrations also showed a gradient of decrease with distance from the production platforms and a correlation with TOC concentrations.

Hydrocarbons and Other Non-metals. The gaseous and volatile components of

the Buccaneer Field produced brine, as described by Brooks et al. (1980b), exhibited considerable temporal variation. Total suspended matter (TSM) in the produced brine ranged from 76 to 529 ppm. Total organic carbon levels ranged from 30 to 49 ppm and were typical of oil-related produced brine. ATP concentration in the brine was negligible, indicating little bacterial biomass. Silicate and phosphate levels of the brine were 324 to 972 μM, and 0.4 to 0.8 μM, respectively, about the same as those for seawater. Low molecular weight (LMW) petroleum hydrocarbons (C_1-C_{14}), including the light aromatics, were found in relatively high concentrations, 23 to 81 ppm, in the produced brine, as they are the most brine-soluble components of petroleum. One-ring aromatics (e.g., benzene, toluene, ethylbenzene, and xylenes) were the major petroleum hydrocarbon components of the produced brine discharge, constituting 70-90% of the C_5-C_{14} hydrocarbons, which had an average concentration of 17 ppm. Such aromatics are the most immediately toxic components of petroleum (Brooks et al., 1980b).

Middleditch (1980) identified 125 substances in the produced brine discharges including n-alkanes, branched alkanes, cycloalkanes, olefins, aromatic hydrocarbons, alkylated aromatic hydrocarbons and sulfur. He observed concentrations as high as 12 ppm of C_{12}-C_{38} alkanes (mean = 3 ppm), 170 ppb of methylnaphthalenes (mean = 43 ppb), 5 ppb of benzo[*a*]pyrene (mean = 1 ppb), and 1200 ppm of elemental sulfur (mean = 460 ppm). The annual discharge of elemental sulfur, a substance with low toxicity, was estimated to be 27 metric tons, more than 100 times the quantity of alkanes discharged. Toxic organic pollutants detected in concentrations higher than 10 ppb were acenaphthylene, benzene, ethylbenzene, naphthalene and toluene. Acrolein (Magnacide B), a biocide used by Shell Oil Company to control sulfur-reducing bacteria populations in the process stream, was not detected in effluents from production platforms.

The composition of the Buccaneer Field crude oil was discussed by Middleditch (1980). Normal alkanes from C_{12}-C_{36} comprised about 18% of the oil and showed decreasing concentration with increasing chain length, giving an odd-even preference ratio of 1.02. Also, LMW n-alkanes comprised 20-40% of the volatile light hydrocarbons (VLH) while the aromatics represented only a few percent. The n-heptadecane/pristane ratio was 0.90 and the n-octadecane/phytane ratio 2.44.

The Buccaneer Field condensate contained about 14% alkanes in the C_{12}-C_{36} range and larger quantities of lighter alkanes than the crude oil (Middleditch, 1980). The n-heptadecane/pristane ratio of the condensate was 1.30, and its n-octadecane/phytane ratio was 3.33.

Petroleum alkanes were detected at the air-sea interface directly below the brine discharge, but were detected only occasionally in other seawater samples, indicating that they were dispersed or degraded rapidly (Middleditch, 1980). Some seawater samples contained bacteriogenic hydrocarbons, which may have been produced by sulfur-reducing bacteria supported by discharged elemental sulfur acting as a nutrient.

The major pool of "fresh" (unweathered) petroleum hydrocarbons and elemental sulfur contaminants from Buccaneer Field operations was the surficial sediments, containing as high as 50 ppm of fresh petroleum alkanes and comparable levels of elemental sulfur (Middleditch, 1980). The 10-fold differences in concentration of petroleum alkanes and elemental sulfur in produced brine were not reflected in the

sediments, so the sulfur must have been dispersed or degraded in a manner different from that of the alkanes. Gradients of decrease in sediment concentrations of petroleum alkanes with distance from production platforms were observed (Middleditch, 1980). He suggested that the sediment concentrations of petroleum hydrocarbon contaminants depended upon the total quantities discharged rather than on concentrations in the discharges, other factors remaining constant. Thus, to reduce the contaminant loads in this pool, both the rate of discharge of produced water and its contaminant loads would have to be reduced. Selected lipids also were detected in Buccaneer Field sediments.

Petroleum hydrocarbons were detected in specimens of barnacles, fishes, penaeid shrimp, fouling mat and other organisms. The particular hydrocarbon fractions found in these specimens were described by Middleditch and Basile (1980b, 1981), Middleditch, Chang and Basile (1979b) and Middleditch, Chang, Basile and Missler (1979). Fishes such as sheepshead that fed on fouling community organisms associated with production platforms contained higher concentrations of petroleum hydrocarbons than those feeding in the water column. Hydrocarbon concentrations in the livers of fouling community grazers usually were higher than in other tissues. Biogenic hydrocarbon concentrations in the biota were usually higher than those of petrogenic hydrocarbons.

Trace Metals. Investigations of trace metals in the Buccaneer Field were summarized by Tillery (1980b) and included aluminum (Al), antimony (Sb), arsenic (As), barium (Ba), beryllium (Be), cadmium (Cd), chromium (Cr), cobalt (Co), copper (Cu), iron (Fe), lead (Pb), mercury (Hg), manganese (Mn), nickel (Ni), selenium (Se), silver (Ag), strontium (Sr), thallium (Tl) and zinc (Zn).

Concentrations of Ba, Cd, Cr, Fe, Hg, Mn, Sr, Tl and Zn in the produced brine discharge were variable, but were higher than in the surrounding seawater in which abnormal concentrations were not detected (Tillery, 1980b). Trace metal concentrations of suspended particulate matter were usually higher than those of surficial sediments, probably a result of smaller grain size and higher total organic content.

Comparing surficial sediments with sub-surface sediments, Anderson et al. (1979) concluded that there were accumulations of Ba, Pb, Sr, Hg, and Zn in surficial sediments within 180 m of a production platform and a well jacket in the Buccaneer Field. Analyses by Wheeler (1979) indicated that there were accumulations of Ba, Sr, Cd, Co and Pb in surficial sediments near the production platform as compared to their concentrations in sub-surface samples and to background levels established by the South Texas Outer Continental Shelf (STOCS) study (Berryhill, 1975). Wheeler (1979) suggested that possible sources of such metals included (1) corrosion of metal structures in the Buccaneer Field, (2) use of sacrificial electrodes, (3) various activities associated with gas and oil field operations on production platforms, (4) produced brine discharge, (5) corrosion of metallic debris on the bottom, and (6) engine exhausts from pleasure boats.

Tillery (1980a, 1980b) detected gradients of decrease in surficial sediment concentrations of Ag, Ba, Be, Cd, Cr, Cu, Hg, Mn, Pb, Sr and Zn with distance (within 100 m) from both production platforms. The observation of such gradients provides circumstantial evidence of a linkage between the production platforms and these sediment constituents. This could indicate that the production platforms

and their operations were possible sources, but other activities associated with transport of materials to and from the production platforms, on-loading and off-loading activities, and recreational fishing and diving activities in the vicinity of the platforms might also be contributing factors. After adjusting the surficial sediment metal concentrations based on known relationships with the hydrated Fe fraction, sediment grain size and total organic carbon concentrations, Tillery (1980a) showed that sediment levels of Ba, Cd, Cr, Cu, Mn, Pb, Sr and Zn were abnormally high, and suggested the same sources of input as those listed by Wheeler (1979). Comparing surficial sediments to sub-surface sediments, and adjusting for Fe concentration, Tillery (1980b) demonstrated an accumulation of Cr, Hg, Pb, Sr and Zn in surficial sediments.

No unusual concentrations of trace metals were detected in fouling community organisms (Tillery, 1980b), even when they were taken in proximity to the produced brine discharge. Trace metal concentrations in muscle tissue of Atlantic spadefish and sheepshead varied seasonally, but showed no unusual accumulation (Tillery, 1980a, 1980b). Muscle, gonad, liver and kidney tissues of Atlantic spadefish and sheepshead showed no unusual burdens of trace metals, with one exception; there were higher concentrations of Ba in gill tissues of obviously diseased fish than in apparently healthy fish. This was believed to result from embedding of the fine-grained sediments within gill tissue rather than from uptake of Ba by the tissues. Muscle tissue of longspine porgy collected in summer had significantly higher concentrations of Cr, Fe, Ni and Pb than did specimens examined in the STOCS study. Tissue levels of Cd in sugar shrimp (*T. similis*) were higher than those observed in the baseline monitoring studies of the Mississippi, Alabama and Florida (MAFLA) outer continental shelf (Alexander, 1977).

Circulation and Hydrography. Armstrong (1980) summarized studies of circulation and hydrography in and around the Buccaneer Field. Thermal stratification occurred during spring and summer and a weak, inverted temperature structure occurred in autumn, with an annual cycle of surface water temperatures closely paralleling that for air temperatures. The winters of 1977, 1978 and 1979 were among the coldest recorded in the last 40 years, as indicated by monthly mean air and surface water temperatures at Galveston, Texas.

Salinities in the Buccaneer Field were lowest in spring, resulting from increased river discharge, and showed a secondary minimum in autumn reflecting the shelf-wide current reversal (Armstrong, 1980). Indications were that discharges from the Atchafalaya and Mississippi Rivers were carried past this region. There was little or no density stratification during most of the year except in spring when a vertical structure developed, characterized by low dissolved oxygen and decreased transparency in the bottom water.

Currents in and around the Buccaneer Field were influenced by alongshore flow toward the southwest (Armstrong, 1980). Layered flow developed in late spring and summer when subsurface currents reversed and flowed to the east. Vector mean current speeds were about 15 cm/sec in the surface layer and about 10 cm/sec near the bottom. Scalar mean current speeds were about 5 cm/sec greater. Current speeds generally were lowest in summer, highest in autumn and almost as high in spring. Flow was most variable in autumn and spring and least variable in summer.

Modeling. Mathematical modeling associated with the Buccaneer Field study included development of (1) a simulation model of biomass flows through the marine ecosystem (Gallaway and Margraf, 1979), (2) hydrodynamic models describing movements and concentrations of suspended and dissolved materials (Smedes et al., 1980; Armstrong, 1980), (3) a hydrocarbon transfer/degradation/accumulation model (Middleditch, Basile and Missler, 1979), and (4) an ecosystem model describing carbon and hydrocarbon flows and storages (Fucik and Show, 1980).

Gallaway and Margraf (1979) developed a 10-compartment model represented by a set of donor-controlled, linear equations, expressed in units of biomass (wet-weight), to determine whether or not the dynamics of the biotic communities associated with a production platform could be explained in terms of resource limitations. Biomass flow simulations indicated that barnacles, sheepshead, Atlantic spadefish and suspended particulate matter should have served as the best indicators as to whether or not hydrocarbons were being bioaccumulated in the system. The model simulated the seasonal dynamics of the fouling community flora reasonably well, but did not adequately depict seasonal dynamics of other compartments. Gallaway and Margraf (1979) concluded that the modeled system was particulate-based and was characterized by high cycling efficiency and high exchange of materials with the environment and that it resembled both estuarine and natural reef systems.

Armstrong (1980), in his review of circulation and hydrography, summarized the findings of dispersion and transport models for Buccaneer Field contaminants as developed by Smedes et al. (1980) and Armstrong (1980). Contaminants were classified as (1) dissolved and suspended, (2) floating and surface film, (3) sinking particulate matter, and (4) resuspended sediment material. The models indicated that any materials other than coarse particulates would be widely distributed and highly diluted. Resuspension events affecting surficial sediments occurred about 9% of the time, so any contaminants accumulating on the bottom eventually would be resuspended and widely dispersed.

The hydrocarbon model of Middleditch, Basile and Missler (1979) showed that concentrations of petroleum contaminants at the air-sea interface and in the water column were greatly influenced by currents and meteorological conditions affecting evaporation. Relatively high concentrations of fresh petroleum alkanes found in the sediments could not be accounted for by dissolution at the surface and diffusion through the water column, but only through some means of active transport. Possible modes of transport included fecal pellets of organisms ingesting fresh petroleum hydrocarbons and adsorption onto elemental sulfur or other particulates.

Considering previously developed hydrodynamic, chemical and biological models, Fucik and Show (1980) revised and updated the conceptual model developed by Gallaway and Margraf (1979) for the marine ecosystem associated with Buccaneer Field. The model of Fucik and Show (1980) differed from that of Gallaway and Margraf (1979) in that phytoplankton was placed in a compartment separate from the holoplankton. Fucik and Show (1980) then developed a quantitative static model and used it to depict annual flows and storages of carbon and contaminants. Results implied that the major flow of material arose from the

phytoplankton, and that advection (that is, materials carried into the system) overshadowed flows between model compartments. Modeled carbon flows were seasonally variable, with greatest flows depicted in spring. The model portrayed trophic dependencies reasonably well, and indicated that 95% or more of the material entering and flowing through the system without being stored exited through the large predators. The model also portrayed the large transport of particulate matter (particularly from plankton feeders) into the benthic compartment, a possible mechanism for the transport of petroleum hydrocarbons into the surficial sediments as proposed by Middleditch, Basile and Missler (1979).

CONCLUSIONS

Impacts of the Buccaneer Field can be classified into those associated with the presence of the structures themselves (Gallaway, 1980) and those associated with the Buccaneer Field contaminants from a number of sources (Wheeler, 1979). The presence of the structures contributed to scouring of surficial sediments (Anderson et al., 1979) and provided artificial reef substrate upon which a fouling community developed and to which a variety of fishes and other motile organisms were attracted or otherwise aggregated (Gallaway, 1980). Fishes and other motile organisms used these sites as sources of food and cover.

The winter season seemed to be unique in that disruption of thermal and density stratification barriers appeared to permit introduction of produced brine contaminants into the sediments, while at the same time winter conditions of mixing of the water column afforded the opportunity for resuspension of sediment contaminants and pathogenic bacteria which bloomed during this season. It was during winter that Atlantic spadefish exhibited external lesions and fin rot in epidemic proportions, presumably the result of seasonal stresses induced by low temperature, change in availability and types of food and exposure to blooms of bacterial pathogens. It was also in winter when high abundance of certain types of fouling organisms produced large quantities of particulate debris and fecal material. Such highly dynamic conditions made it extremely difficult, if not impossible, to determine cause and effect relationships, but the complex interactions among the physical, chemical and biological factors during winter may well be one of the most promising lines of investigation in future pursuits aimed at detecting impacts of gas and oil fields on the marine ecosystem.

The Buccaneer Field study suggests that future assessments of impacts of offshore gas and oil production operations should concentrate on the components of the marine ecosystem in and around the production platforms and associated structures. The Buccaneer Field investigation was unable to detect impacts beyond 100 m from production platforms. Studies that do not include sampling in close proximity to the point sources of gas and oil field contaminants are not likely to detect significant impacts, when compared to regional background levels of contaminants in the marine ecosystem. The biological communities developed on or around offshore structures are in many cases "captive communities." Sessile organisms either do not survive or they become adapted to the particular levels of chronic contamination characteristic of a particular operation. They may show seasonal variations in biomass, some of which may be related to seasonal changes in susceptibility to discharge contaminants, and certain biological functions may be

suppressed in the immediate vicinity of the contaminant discharge. While many motile organisms become habitat faithful, they can avoid the highest concentrations of contaminants by choice. However, once they become associated with the gas and oil field structures (through recruitment or migration) they may be reluctant to move away due to lack of other suitable habitat in the area. A gas and oil field may offer structures without contaminant discharges (well jackets) as well as those releasing contaminants (production platforms, quarters platforms and flare stacks). Depending upon distances among these structures, motile organisms may choose relatively uncontaminated structures of comparable habitat within the same general area.

Finally, not only are various biotic communities attached or attracted to artificial reefs represented by gas and oil field structures, but recreational fishermen and divers concentrate their activities near these structures, thus subjecting important reef fish populations to heavy fishing pressures and making them more vulnerable to fishing. An advantage may be that the heavy fishing pressure reduces the residence time of such "captive" fish populations, thus reducing the amount of time that individual fish are exposed to contaminants, allowing less time for possible bioaccumulation of contaminants that may be harmful to man.

DISCLAIMER

This paper has been reviewed and approved by the National Oceanic and Atmospheric Administration, National Marine Fisheries Service and the Environmental Protection Agency. However, such approval does not signify that the contents necessarily reflect the conclusions, views and policies of NOAA, NMFS or EPA. Mention of trade names or commercial products herein does not constitute endorsement or recommendation for use.

ACKNOWLEDGMENTS

Those responsible for developing, initiating and participating in the environmental assessment of the Buccaneer Field are far too numerous to acknowledge individually here (see Table 1). Especial recognition is due Dr. J.W. Angelovic, Deputy Director, NOAA Ocean Programs Office, Washington, D.C., who as former Director of the NMFS Gulf Coastal Fisheries Center in Galveston, Texas, was instrumental in developing and initiating the project in 1975.

We are grateful to Mr. J.B. Rucker, NOAA Research and Development, and Mr. W.L. Pugh, NOAA Ocean Programs Office, Washington, D.C., who as Program Managers for this EPA/NOAA/NMFS project, provided overview, guidance and administrative support to the project.

We also are grateful to Dr. E.F. Klima, Director, NMFS SEFC Galveston Laboratory, whose guidance, encouragement and support were instrumental in providing the opportunity and atmosphere within which such scientific and technical investigations can flourish.

Especial thanks are due Mr. J.A. Burgbacher, Offshore Division, Shell Oil Company, New Orleans, Louisiana, whose cooperation and assistance facilitated field work in the Buccaneer Field.

To past and present members of the staff of the Environmental Research Division of the NMFS SEFC Galveston Laboratory who contributed to the study, we are especially indebted. B. Richardson and P. Prado typed the manuscript, and D. Patlan prepared the figures.

Contribution No. 81-09G of the Southeast Fisheries Center, Galveston Laboratory, Galveston, Texas 77550.

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